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Workshop on the Design and Control of Dexterous Hands

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ABSTRACT.

The Workshop for the Design and Control of Dexterous Hands was held at the MIT Artificial Intelligence Laboratory on November 5-6, 1981. Outside experts were brought together to discuss four topics: kinematics of hands, actuation and materials, touch sensing, and control. This report summarizes the discussions of the participants, and attempts to identify a consensus on applications, mechanical design, and control.

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1. Introduction

This is a report on the Workshop for the Design and Control of Dexterous Hands held at the MIT Artificial Intelligence Laboratory on Nov. 5-6, 1981. Research in dexterous hands for manipulators is a relatively new area of robotics which is now developing rapidly, impelled both by research imperatives and applications needs. The lack of capabilities of current manipulator end effectors is increasingly perceived as limiting potential robotic applications. Dexterous hands is an exciting field with still many unsolved problems in both mechanical design and control.

The confluence of activity at major research centers attests to the timeliness of this topic for a workshop. The number of researchers in this new field is small, and they are dispersed at a few centers around the country. These researchers were brought together at this early stage of development of the field to exchange experiences gleaned from past efforts and ideas about future directions of research, with the hope that the workshop would lay grounds for future collaboration and cooperation as research in this area progresses.

This workshop was held in conjunction with the Year of the Robot program at the MIT Artificial Intelligence Laboratory. The program, which is sponsored jointly by the Office of Naval Research and the Defense Advanced Research Projects Agency, has as a goal the enhancement of robotics activity at MIT in several dimensions over a five year period. Two major projects have been launched within the Year of the Robot program, one the design and control of dexterous hands and the other the design and implementation of a task level manipulator control language.

The dexterous hand project is a two-year program for the design, construction and control of a multi-fingered hand with the collaboration of Steve Jacobsen and John Wood from the University of Utah. This hand project is attempting to push the state of the art with respect to materials, actuation, sensing, and control, while benefiting from the results of predecessors, many of whom were present at the workshop. Another reason for the workshop was to examine the many aspects of a hand project directly in the presence of these outside experts, with the hope that some consensus on a design specification could be reached.

In the remainder of this report comments by a participant will be referenced by stating the participant's

name, whereas a literature reference will be distinguished by author name and date in brackets. The topics discussed here do not directly reflect the workshop sessions, but have been reorganized for clarity and cohesion.

2. Applications Imperatives

Current end effectors limit the flexibility and capability of manipulator systems, due to the lack of arbitrary parts handling and sensing abilities. The most common end effector is a parallel jaw gripper, which while capable of a number of tasks nevertheless limits the kinds of objects which may be grasped and the ways in which they may be manipulated. The use of parallel jaw grippers has been likened to a car mechanic using only pliers to execute all repairs, such as holding a screw driver with the pliers [Crossley and Umholtz 1977]. Current end effectors most frequently lack any touch or force sensing ability as well, which is necessary for detecting stable grasp, slippage, exact object position, and environmental interactions. We can liken this lack of sensory input to our own experiences in attempting fine manipulation tasks with numb fingers.

There are far-ranging effects from end effector limitations, including a need for special purpose hands, a requirement for precise automatic jigging for parts presentation, and a predominance of non-contact applications. Economic arguments have been presented against the use of special purpose hands. In a varied task where a robot would have to switch hands for different aspects of the task, Skinner [1975] has argued that the extra time required to switch hands will ultimately make this solution less economically efficient than a solution involving a general purpose hand that can accomplish all tasks. Moreover, Ken Salisbury pointed out at the workshop that the cost of special purpose hands is often as much as the manipulator itself, so that a battery of special purpose hands could become prohibitively expensive.

In current practice there is almost no assembly being done by robots in industry, due to an inability to monitor interactions with the environment, to limitations in planning and control systems, and to a lack of the positional accuracy and resolution to do assembly by dead reckoning. The vast majority of robotic uses in industry involves applications such as spot welding and spray painting which do not involve contact. The positioning requirements of these tasks is low, and it is unnecessary to monitor interactions with the

environment.

In assembly operations, incremental movements are required for precise parts mating. Because current industrial manipulators usually have at most six degrees of freedom, general incremental movements can only be accomplished by activating all the joints, including the largest joints furthest removed from the task. Due to mechanical or control impediments, small incremental movements are not possible with such large joints. In analogy with the human arm, Ken Salisbury noted that a multi-fingered hand with an incremental movement ability would permit compliant assembly operations without involvement of the large joints. The large joints of the manipulator would then serve only to bring the hand into the vicinity of the assembly operation, which would be completed by precision movements with the fingers. Passive compliance such as with a Remote Center Compliance device [Drake 1977] can accomplish close-tolerance peg-in-hole insertion, but such devices are specific to a task and of course are not useful in general grasping.

Even if manipulators were sufficiently accurate, pure position control of manipulators requires that parts be presented to manipulators in predictable positions and orientations. The precise jigging and parts feeding needed to accomplish automatic parts presentation is often more expensive and more difficult to set up than the manipulator itself. Because the automatic parts presentation is specific to a particular task, the promise of flexible automation with robots is defeated and the manipulator/feeder system becomes just another form of fixed automation. While the parts presenters in current use, such as vibratory bowl feeders, pallets, and conveyer belts, are adequate for a variety of parts, there are many parts which cannot be conveniently accomodated by them. Parts presenters also require a lot of space, a severe problem for some manufacturing facilities. Vision could help to some extent if it were fast and general, which it is not yet, but ultimately vision which is non-contact sensing must be considered complementary to the contact sensing of force and touch.

Besides a requirement for precise parts presentation, another reason for fixed jigging is as a fixture for firmly holding parts while operations are performed on them by the manipulator. Just as special purpose hands are currently needed to permit different operations by the manipulator, even so a special purpose fixture is required for holding a particular part. With a dexterous hand capability, a manipulator could serve as an

adaptable and active fixture as well. Two manipulators could then work together in an assembly operation, one holding a part while the other performs an operation on it.

With a dexterous hand capability, robots could be removed from stereotyped situations such as assembly lines. The elimination of elaborate parts presenters would convert essentially fixed automation with robots into the desired flexible automation. Economics would then justify smaller batch runs with robots. Non-assembly operations such as maintenance and repair would become feasible. Further discussions of the applications and economics of hands and tactile sensors may be found in [Harmon 1980, 1981].

3. Mechanical Research Imperatives

Dexterous hand design places severe demands on technology, even as hand control brings a host of new problems to the robotics field. Mechanical impediments exist at all levels, including actuation, transmission, materials, and sensing. We need only think of the large, heavy, and slow manipulators of today to appreciate the scope of the problem in building a very small multi-manipulator, with three or four degrees of freedom for each of several fingers. Clearly the current robot technology cannot be directly applied to manipulators of this reduced scale; rather, a whole new technology is needed.

The question of biological duplication always arises in robotics, and nowhere more strongly than in multiple-fingered hands with touch sensing. Roth argued against attempting to duplicate the human hand, suggesting that aspects of hand design should be adapted to particular tasks because there may be no best hand. Jacobsen argued that the biological system has much to teach us, and that an understanding of this system would be useful in constructing artificial hands even if the final system departs substantially from the biological system.

3.1 Actuation and Transmission

Current actuation technology provides perhaps the most serious, long term impediment to hand design. Aspects of torque, weight, size, and power consumption of modern actuators are not favorable for hand

design, especially when compared, as any artificial hand system inevitably must, to the muscles of the human hand in particular and of the human body in general. John Wood pointed out, for example, that human muscle operates most efficiently at stall whereas torque motors require their maximum power at stall. The length-tension properties of muscle, moreover, provide automatic stability during torque production whereas stability with torque motors must be provided by a feedback controller. Carl Ruoff argued on the other hand that sensor-based control allows cheap actuators, so that perhaps the requirements on finger actuators are not too severe.

The main candidates for hand actuators are electro-hydraulic actuators and electric torque motors. The ultimate feasibility of electro-hydraulic actuators is still a matter of opinion because of continuing improvements in these systems, but Steve Jacobsen mentioned that in his experience electro-hydraulic actuators have always promised more than they delivered. The enticement of favorable strength to weight ratio is subverted by some unwanted complexity elsewhere. Flatau [1973], in discussing design concepts for the construction of small manipulators, mentioned three problems in making hydraulic actuators small: (1) seal friction becomes predominant for small actuators; (2) leakage rates approach full flow rates; and (3) small valves are extremely sensitive to particle contamination.

Electric torque motors and stepping motors are much more readily controlled, yet there are problems. Stepping motors are large and heavy relative to their strength, although Jacobsen noted that there have been recent improvements which could make stepping motors as attractive as torque motors. Rare earth motors have appeared recently with magnetic fields several times stronger than previous torque motors, although Flatau [1973] argued against miniturizing samarium cobalt motors because they need large air gaps to overcome narrow and high hysteresis curves. For the time being it was generally agreed that electric motors were the best actuators for a tendon drive system. But ultimately electric motors are limited by the maximum possible magnetic field strengths, and in Steve Jacobsen's opinion, unless some totally new breakthrough in magnetic materials occurs, electric torque motors will fail to satisfy the stringent requirements imposed by hand design.

Closely allied with actuation is transmission, namely the method by which force or torque from the actuator is applied to the manipulator joints. The most common methods of transmission include gears (the MIT Vicarm), drive axles (the PUMA arm), tendon/pulley systems (teleoperator arms), lead screws (the MIT Purbrick arm), chains (the Hitachi arm), and rod/cam systems (the ASEA arm). Whereas many current manipulators have motors mounted directly at the joints, this option is not feasible for hand design because the fingers would be too bulky and the added weight from the motors would make the hand too heavy. A remote transmission scheme, and a tendon scheme in particular, seems called for. Yet when looking at current tendon technology, Steve Jacobsen notes certain problems. Steel cables have a minimum bending radius which limits compactness. Routing of tendons with pulleys over several joints can be a nightmare, especially for systems which are not pretensioned and for which a slack tendon may fall off the pulley. Boden cable technology (i. e. bicycle cables) avoids pulleys but brings severe friction problems of the tendon against the sheath. Once again the human hand serves as a benchmark for tendon systems. Not only is the system self-healing (which automatically combats wear), but John Wood notes that the combination of sinuvial fluid with the tendon/sheath system gives nearly the lowest coefficient of friction known to man. With Steve Jacobsen (see below), he argued for a tendon tape transmission system analogous to the human sytem.

3.2 Materials

Materials usage in current manipulators has not caught up to the space age. Bicycle construction, as a counterpoint, has encompassed such modern materials as titanium tubing, carbon fiber reinforced plastics, and special alloy aluminum tubing welded with special techniques. It would seem that the steel and aluminum used in current manipulators will eventually have to give way to special materials such as plastics in order to make the compact, light hands of the future.

Steve Jacobsen reported on some preliminary experiments in designing tendons with tapes rather than with cables. Noting first that tapes had a smaller minimum bending radius than round wire cables, Jacobsen also remarked that wider tapes had a superior fatigue life relative to narrower tapes because of a lubrication

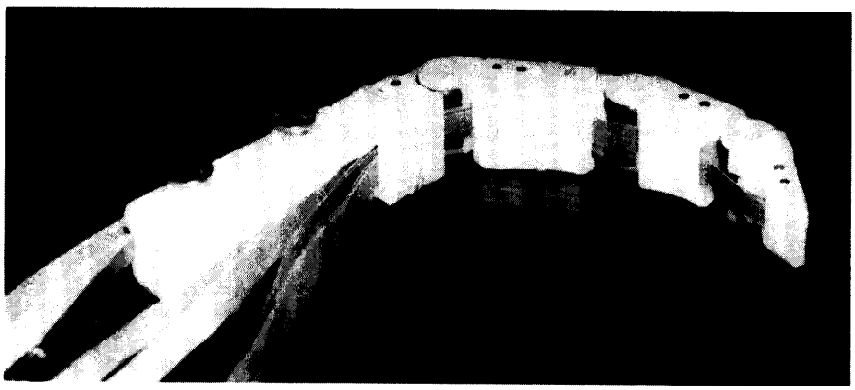

Figure 1. Prototype three-degree-of-freedom finger with six tendons designed by Steve Jacobsen and John Wood and incorporating novel tendon tapes, tendon routing scheme, and joint structure.

containment effect: the edges of the tape sealed in the lubricant underneath the tendon tape. Other important factors considered in these initial designs were the tendon strand weave, the tendon coating material, and the running surface for the tendon. Carl Ruoff suggested hardened bushings instead of pulleys for passing tendons over joints.

Better integration of the transmission system with the materials and structure of the linkage system seems necessary. Jacobsen suggested that links could be constructed from injection-molded plastic with built-in channels for tendon routing. The links could be hollow for routing electrical wires, and could be designed to snap together. He proposed a double toroid joint structure, which is the human finger joint structure, with low wear and low friction surface coatings. Not only does this joint structure avoid using heavy ball bearings, but it also provides considerable sideways stability. An initial prototype for such a finger with three degrees of freedom and six tendons is shown in Figure 1.

3.3 Sensors

The design of force and touch sensors encounters problems of materials, sensitivity, and compactness. Harmon [1981] has listed requirements for a tactile skin: robustness, low hysteresis, a spatial resolution of 1

mm, sensitivity of 1 gram, a dynamic range of 1000:1, a time resolution of 10 msec, and monotonic response if not linear. Various methods of fabricating tactile sensors were reviewed [Harmon 1980, 1981], and the conclusion of these reports is that current technology is far from satisfying tactile requirements. Sensor technology has also been reviewed by Binford [1972]. One of his suggestions is that sensors need to be near the surface without too much intervening material to avoid hysteresis and loss of sensitivity.

Danny Hillis reported on a conductive rubber sensor [Hillis 1982] which does satisfy many of the requirements listed by Harmon. The sensor has sufficiently high resolution at 256 points per square centimeter, compared to a human fingertip resolution of 280 points per square centimeter [Johannson and Vallbo 1979]. The sensor also has a gram sensitivity but a restricted dynamic range, and the response to pressure is monotonic. Hillis suggested that the dynamic range could be improved by fabricating a sensor with several layers of conductive rubber with different separations between layers. The sensor has low hysteresis because of the thinness of the conductive rubber. To increase robustness Hillis suggested placing a protective covering over the sensor, although this decreased the sensitivity somewhat. Because of the resistive basis of operation, however, there are difficulties in making the sensor much larger, and probably the sensor would have to be deployed as independent patches. Figure 2a shows a picture of the Hillis sensor, and Figure 2b is a tactile recording of a small washer.

A serious problem with high resolution touch sensors is the number of wires emanating from the sensors. One possibility for dealing with the wire problem is to do some tactile processing at or near the sensor in the finger, and to transmit features rather than tactile intensity arrays [Raibert 1982]. There have been some tactile sensor designs based on fiber optics, and if such designs ever prove successful they would have advantages in cabling over conductive wire designs. Yet another problem is fitting the sensor to the finger. Unlike the simple geometry of parallel jaw grippers, fingers are more likely to have a complex shape. Aside from detailed incorporation of a tactile sensor into the finger structure, an attractive possibility would be a touch-sensitive skin which could be slipped on like a glove.

The consensus at the workshop was that it is premature to incorporate touch sensors into hand designs

Figure 2. A) The Hillis touch sensor with 256 tactile elements per square centimeter. B) A tactile recording of a small washer.

given the current state of development. Nevertheless provisions should be made in the hand designs for later addition of touch sensors.

4. Control Research Imperatives

The control of a multiple-fingered hand has some resemblance to the coordination of multiple manipulators, save that contact with objects is obtained with the frictional surface of fingers instead of with grippers. Stable prehension of objects with a multi-fingered hand requires precise application and balance of forces and torques through the frictional surface contacts of several fingers with the object. New control issues emerge from this relatively flexible contact, broadly involving the interaction of design and control, the processing of touch information, and methods of prehension.

4.1 Interaction of Design and Control

The kinematics of the finger linkage structure and of the finger attachments to the hand influence workspace and finger object motions. Bernie Roth, in mentioning that the kinematics of arms applies to hands as well, introduced the notion of *void* and *hole*. Generally speaking, the workspace of most manipulators is

donut-shaped. A void is any empty space inside the toroid that cannot be reached, while a hole is the donut hole that cannot be reached. To maximize workspace, one has to try to eliminate voids and holes, but of these two spaces holes are a severer problem. In particularizing to hand kinematics, Roth noted that a two-degree-of-freedom knuckle reduces voids. To reduce holes Roth mentioned the rule that if the most distal link is of length a and the next link is of length b, then the third link should have a length $a + b$.

In terms of finger-object motions, Ken Salisbury noted that there are certain points in the workspace where forces can be exerted and incremental finger movements can be controlled most accurately. He suggested that the *condition number* of the Jacobian can serve as a measure of this accuracy and defined *isotropic points* as places where the condition number is at a minimum. Salisbury designed his hand (Figure 3) so that the isotropic points of the three 3-degree-of-freedom fingers were situated on a grasped one-inch sphere. Thus his hand design has been optimized to grasp objects of roughly this size, although larger or smaller objects can also be grasped with a certain loss of precision in incremental movement ability. The finger degrees of freedom were shown adequate to arbitrarily grasp an object and to carry out fine compliant motions with the object.

Whether a finger requires three or four degrees of freedom was a topic discussed without resolution at the workshop. In examining the human hand, participants differed whether the human finger really has four functional degrees of freedom or whether the movement of the last link is coupled to that of the previous link. Roth noted that an extra degree of freedom allows orientation flexibility, so that a given point could be reached from a given direction by one or more fingers. Other reasons for a fourth degree of freedom include more flexible control, better wrapping of a finger around an object, and improved obstacle avoidance in the sense of being able to reach around object protuberances to find a grasp point. Ken Salisbury felt that at the present time the added mechanical complexity did not warrant a fourth degree of freedom.

Three fingers represent the simplest kinematic arrangement that allows an arbitrary grasping ability, but hand designs with more than three fingers would yield extra functionality. For the human hand, fourth and fifth fingers are used in a power grasp, whereas the first three fingers are more involved in fine manipulations.

Figure 3. The Stanford-JPL hand with three fingers with three degrees of freedom each. Tendons have been connected to one of the fingers; this design follows the $n+1$ rule.

The last two fingers also serve as a pad for resting the hand on a surface, a strategy which allows the most precise hand control. The fourth finger degree of freedom becomes useful here because the last link forms the pad. Combined grasping and finger operations are made possible, with some of the fingers of the hand performing the grasp and other fingers some operation on the grasped object (e. g. using an electric hand drill). Object reorientation would be easier, with three fingers grasping the object and the other two finding grasp points suitable for turning the object. Naturally the extra fingers also provide a securer grasp, with more fingers wrapping around an object.

The number of tendons, the tendon routing, and the tendon branching influence the control of each finger. None of the conference participants advocated a belt tendon arrangement, with each degree of freedom controlled by one tendon belt. Carl Ruoff noted that a pull-pull arrangement avoids the pretension requirements of a tendon belt; pretensioning adds friction and reduces force resolution. Moreover, the number of

required tendons is only one greater than the belt arrangement due to the so-called $n + 1$ rule, which states that an n degree-of-freedom finger requires only $n + 1$ tendons for actuation. Steve Jacobsen mentioned control advantages which arise from a co-contraction regime, such as independent control of torque and stiffness.

A controversy arose over this $n + 1$ rule. Noting the advantages of a scheme with the fewest number of motors, Ken Salisbury has applied the $n + 1$ rule to his finger design. Steve Jacobsen and John Wood on the other hand mentioned stability problems with an $n + 1$ design, such as a buckling tendency under certain conditions. Based on the state of current understanding of control, he argued for a design somewhere inbetween $n + 1$ and $2n$ that incorporates tendon splitting.

Steve Jacobsen and John Wood noted that tendon routing and branching may be used to perform geometrical computations. The branching of human finger tendons and the various places the tendon branches pass over a joint all have meaning, and can be shown to provide a form of joint coordination. Neville Hogan noted that the role of two-joint tendons in the human arm may be to assist in setting preferred directions of compliance.

The surface material or "skin" of the fingers influences how the hand may be used. Tomas Lozano-Perez suggested that a deformable skin might best suit prehension requirements, since a soft skin would adapt more readily to an object shape and provide a larger frictional surface of contact. In a sense each finger contact pad would act as a small palm, a frictional platform for object support, instead of as a point source of forces and torques. Crossection information from a deformable skin sensor obtained by increasingly pressing on an object can yield haptic judgments of surface shape. A rigid skin on the other hand might best serve haptic judgments of object position, since a soft skin leaves some uncertainty about how the object is situated with respect to the finger. With respect to this latter point about position uncertainty, Carl Ruoff noted that a fundamental change in approach is needed for hands with a soft surface.

Allied with surface material is the finger shape. The argument presented for a cylindrical shape was that the point of contact between finger and object is the most controlled and predictable. Binford [1972] noted that

round fingers concentrate force and enhance sensor sensitivity. Nevertheless Roth, in noting more generally that there may be no best hand, suggested that finger shape should be dictated by the set of tasks.

Other design decisions that influence control are the existence of a palm, of fingernails, and of fingerprints. A palm would provide a large surface or "table" for resting an object [Rovetta and Casarico 1978, Rovetta 1979], and it could also serve as a "backboard" for dynamic grasps such as catches. Fingernails would permit picking up thin objects such as washers [Crossley and Umholtz 1977]. There was speculation about the role of fingerprints in the human hand, with one hypothesis that fingerprints serve to break vacuum or suction effects on the grasping surfaces. Alternatively, Richards [1979] has proposed that fingerprints provide ridges used in estimating spatial frequency when a finger is moved across a surface.

4.2 The Processing of Tactile Information

To some extent current investigation of artificial tactile sensing is paralleling the history of vision research. It is natural that many of these early studies focus on contour extraction from primarily flat object surfaces with single time-invariant tactile images. Orthodox pattern recognition techniques have been applied [Okada and Tsuchiya 1977]. Some [Briot 1979] are reminiscent of recent binary vision systems such as the SRI Vision Module [Agin 1980]. Issues of model-driven perception versus low-level feature extraction have rearisen [Hillis 1980]. With regard to this point, Mike Brady cautioned against repeating vision research history, arguing that there should be levels of low level touch processing.

Hillis [1982] extracted three features from tactile information to distinguish between a collection of fasteners which included machine screws, dowel pins, cotter pins, set screws, lock washers, and flat washers. Combinations of the three features, namely aspect ratio, the presence of holes or bumps, and rollability, were sufficient to distinguish among these objects. Ruzena Bacjsy recounted some investigations to distinguish basic planar shapes with a Lord Kinematics touch sensor, which has an array of touch-sensitive knobs spaced at 0.3 inch centers. She noted that the coarse cell size made recognition of comparably sized objects difficult.

It is presently unclear as to how the low-level processing of touch should be done. It is an open question

whether models for early vision processing may serve as direct prototypes for tactile processing. Richards [1979] argues that the independent channel structure of early human vision applies not only to touch but to audition as well. Certainly tactile information is analogous to visual information, insofar as both involve a large array of time-varying intensity values and both are attempting to ascertain some of the same information such as surface shape, texture, and material. Unlike vision, tactile perception is not supported by a large body of psychophysics to guide model development, although research in this area is continuing. [Johansson, Landstrom, and Lundstrom 1982], for example, mention that edge enhancement occurs through the mechanical properties of the receptors, in addition to any neuronal inhibitory surround mechanisms. Phillips and Johnson [1981] have proposed a skin model which predicts mechanoreceptor responses to bars, edges, and gratings.

There are a number of ways touch sensing can be used and combined with finger movements. Slippage and stability of grasped objects can be inferred from sensor readings. Single tactile images from a single finger can yield local information about surface shape and texture. More global shape information can be obtained by moving the finger along the surface [Kinoshita et al. 1975]. When tactile information is combined with a knowledge of finger position, objects may be located precisely. Sensor and position readings from multiple fingers yield shape and position information on a larger scale [Kinoshita 1977].

Clearly tactile information processing is a relatively new research area that may see rapid development in the current decade. Until now the lack of adequate touch sensors has inhibited research into this area, as well as a multi-fingered hand for general placement of touch sensors around an object, but such sensors as the Hillis touch sensor make this research viable.

4.3 Methods of Prehension

Stable prehension of arbitrary objects is a basic ability required of a dexterous hand. When stable prehension is coupled with an incremental movement ability, it is possible to perform compliant assembly operations using only fine movements of the fingers. More difficult prehension methods such as object reorientation and

dynamic grasping require stable prehension as a building block.

The first step in stable prehension is determination of finger placement on an object. Hari Asada analyzed finger placement for the special case of two-dimensional objects and single-degree-of-freedom fingers with frictionless contacts. By defining a potential function formed from spring-like finger forces, Asada showed how fingers could be optimally placed on an object contour so as to minimize this potential function and hence to grasp the object stably.

In considering prehension for 3-dimensional objects, Ken Salisbury did not directly address the finger placement problem but argued that stable prehension could be achieved in principle by limiting object mobility through frictional contacts with three fingers. While these works on finger placement represent significant steps towards a general solution, it is nevertheless clear that further work is required for the case of three-dimensional objects with friction. Matt Mason discussed movement of objects in the presence of friction, which bears on a more general solution, and in particular introduced a *center of friction* concept for an object resting on a frictional surface.

After determining the grasp points, coordinated finger action is required for an incremental movement ability. In synthesizing a finger coordination strategy, Asada considered a multi-fingered hand in which each single-degree-of-freedom finger contained a passive leaf spring and was activated by a stepping motor which pulled on the finger like a lever (Figure 4). Interestingly this mechanism is analogous to a spring muscle model used by Emilio Bizzi [e. g. Bizzi, Polit, and Morasso 1976] in his work on biological motor control, insofar as a muscle is modeled as a spring with tunable zero setting. The movement of the stepping motor corresponds to selecting a new zero setting for the passive leaf spring. The finger forces arise from a combination of passive stiffness from the spring and an active stiffness from zero setting control. By considering object geometry, Asada related the net force and moment on the object to finger forces and positions. A desired object compliance was then synthesized by relating the net force and moment to an object stiffness matrix.

John Craig presented a hierarchical controller which achieves an incremental movement ability for the Stanford/JPL hand by exerting forces and torques on the object through a remote center of compliance. The

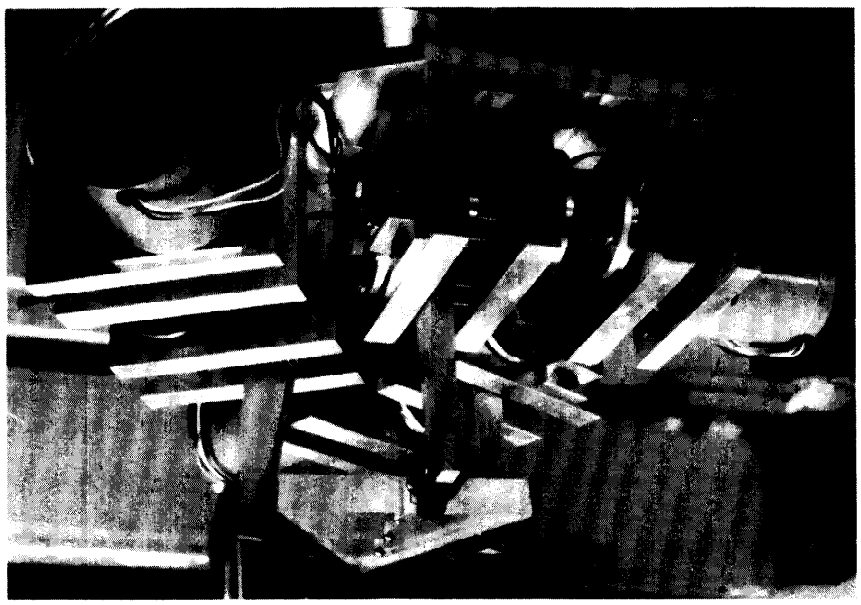

Figure 4. A three-fingered hand designed by Haruhiko Asada to grasp planar objects stably and to execute incremental compiant motions. Each single degree-of-freedom finger is actuated by a stepping motor, and contains a passive leaf spring..

lowest level in the hierarchy is a tendon controller which achieves commanded forces in conjunction with feedback from a special force sensor on the tendon. The intermediate level is an individual finger controller which takes commanded finger forces and transforms them to tendon forces. The top level of the hierarchy coordinates finger movement by converting desired positions, velocities, and forces in Cartesian space to commanded finger forces. A novel feature of this controller is that the inverse Jacobian is not required, due to the feedback control at the Cartesian level and the resolution of Cartesian forces to joint torques.

While stable grasp and incremental movement were extensively discussed at the workshop, object reorientation was only briefly mentioned, due no doubt to the difficulty of analysis. Object reorientation could be accomplished statically if there were a palm or extra fingers, so that stable grasp methods could be directly applied. Alternatively object reorientation could be accomplished dynamically, by essentially throwing the object with spin and catching it in a better orientation. Nevertheless it is clear that our understanding of object

reorientation and dynamic grasping is primitive and will provide a challenging area for future hand research.

Conclusions

This workshop saw the presentation of hand designs, tactile sensors, and control concepts which represent significant developments in this new field. A three-fingered hand design was presented that was based on a careful analysis of how workspace and differential motions could be optimized in the design; the hand's hierarchical controller permits both independent finger control and coordinated finger action as in generating small compliant motions of a grasped object. Another hand design and control methodology was presented for determining stable grasps for planar objects and for executing compliant motions while maintain grasp stability through a finger coordination strategy involving a combination of active and passive stiffness regulation. Proposals were made for improved tendon systems and for finger link and finger joint design and construction. Also, a high-resolution tactile sensor was presented along with its use in object shape recognition.

A variety of issues arose which will require further study. Some kinematic issues were the number of fingers per hand, the number of degrees of freedom per finger, and the number of tendons per finger. Mechanical issues centered around choice of motors. While electric motors were generally favored as actuators, there was still hope that hydraulic actuators would eventually prove suitable. More general issues were the extent to which human hand biomechanics should guide our thinking about robot hand design, and whether one should design one single general purpose hand or whether there should be different hands for different purposes.

The workshop identified further areas in control and in processing force and tactile information for which advances are required. It is not yet understood how to process information from a single tactile pad, how to integrate this information into individual finger control, and how to combine information from several finger pads to guide hand action. Control areas requiring further study are the determination of a general stable grasp in three dimensions in the presence of friction, and the development of more advanced hand control strategies such as object reorientation and dynamic grasping.

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